Strategic Knowledge Gap	Narrative (modified from LEAG 2012 GAP SAT report)	Enabling or Enhancing	Status	Exploration Science or Technology	Messurements or Mission needed to retire SKG	Notes 2016 Assessment
III-A-1 Technologies for excavation of lunar resources	Collect raw materials; create trenches, roads, berms, etc.; enables ISRU, surface trafficability, and ejecta plume mitigation.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, at both polar and non-polar locations, and at different resource deposits (e.g., polar ice-bearing regolith, regional pyroclastic deposits), testing resource excavation techniques, are required to retire this gap.	University competition at KSC involving regolith manipulation. Demonstrations at Hawaii (PISCES) NASA ISRU types: Sanders, Mueller, Sacksteder, Linne Open University 3-D printing with lunar regolith (Mahesh Anand)
III-A-2 Technologies for transporting lunar resources	Load, excavate, transport, process, and dispose of regolith; enables ISRU, surface trafficability, and ejecta plume mitigation.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, at both polar and non-polar locations, testing the transportation of lunar resources, are required to retire this gap.	University competition at KSC involving regolith manipulation. Demonstrations at Hawaii (PISCES) NASA ISRU types: Sanders, Mueller, Sacksteder, Linne Open University 3-D printing with lunar regolith (Mahesh Anand)
III-A-3 Technologies for comminution of lunar resources	Crush, grind regolith; understand effects of comminution; enhances ISRU process efficiency.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, at both polar and non-polar locations, testing the communition of lunar resources, are required to retire this gap.	University competition at KSC involving regolith manipulation. Demonstrations at Hawaii (PISCES) NASA ISRU types: Sanders, Mueller, Sacksteder, Linne Open University 3-D printing with lunar regolith (Mahesh Anand)
III-A-4 Technologies for beneficiation of lunar resources	Sort regolith by material properties (e.g., particle size, density, mineralogy); some techniques utilize gravity and magnetic separation; enhances ISRU process efficiency.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Experiments on the lunar surface, at both polar and non-polar locations, testing the beneficiation of lunar resources, are required to retire this gap.	University competition at KSC involving regolith manipulation. Demonstrations at Hawaii (PISCES) NASA ISRU types: Sanders, Mueller, Sacksteder, Linne Open University 3-D printing with lunar regolith (Mahesh Anand)

Strategic Knowledge Gap	Narrative (modified from LEAG 2012 GAP SAT report)	Enabling or Enhancing	Status	Exploration Science or Technology	Messurements or Mission needed to retire SKG	Notes 2016 Assessment
III-B-1 Lunar geodetic control	Combine SELENE, ULCN2005, LRO LOLA, and LRO WAC GLD100 topographic products to produce a definitive lunar geodetic grid to facilitate future exploration planning**.**	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Exploration Science	No additional measurements or missions are needed to retire this exploration science gap. Sufficient data exists from the LRO mission to close this gap. However, the effort to create this geodetic grid has not been funded. Adequate funding would retire this exploration science gap.	Sufficient data exists from the LRO mission to close this gap exists. However, the effort to create this geodetic grid has not been funded. Integrating international datasets makes this complex. Closing this SKG is a multi-year effort (i.e. 3 yrs.) needing several $100K. People to talk to: Sam Lawrence, Brent Archinal
III-B-2 Lunar topography data	LRO data (LOLA and LROC WAC) has produced substantial improvements in lunar topography, providing two independent global topographic datasets with ~200 m/pixel resolution, which enables many exploration missions. An LRO extended mission of at least 5 years duration (i.e., to 2017) will enable collection of a definitive global DTM with 1-2 m/pixel resolution using the LROC Narrow Angle Cameras.	Enhancing for all missions.	**OPEN**	Exploration Science	Possibly, continued LRO extended missions until fuel runs out. Constructing a global 1-2 m/pixel DTM would require a large amount of computer processing and software capabilities not presently available, but additional research may enable creation of this dataset. This is "enhancing" because regional stereo observations exist or can be collected for numerous high-priority exploration destinations.	The current LROC and LOLA datasets are sufficient to create regional DTMs. Is there really a need for a global DTM with 1-2 m/pixel resolution? Most on the SAT don't think so. Sam Lawrence, Brent Archinal, Mark Robinson

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III-B-3 Autonomous surface navigation	Ability to remotely traverse over long distances enables a) pre-positioning of assets, and b) robust robotic precursor missions. Requires sliding autonomy and localized hazard avoidance technology (e.g., DARPA Grand Challenge). Significant development work can be performed on Earth prior to lunar surface deployment.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, at both polar and non-polar locations, testing autonomous surface navigation, are required to retire this gap. A lunar GPS constellation may be required.	Teleoperation of Ames K-10 rover by ISS crew. Limited autonomous traverses (10s of meters) by Sprit, Opportunity, and Curiosity on Mars. Other terrestrial robotic traverses? (e.g., CMU Atacama desert traverses) People to talk to: NASA robotic types at JSC, Ames, JPL; Lunar Catalyst types such as Red Whittaker
NEW PROPOSED III-B-4 Autonomous Landing and Hazard Avoidance	Autonomous landing capability for robotic missions similar to that demonstrated by Chang'e-3 lander.	Enhancing for all missions.	**OPEN**	Technology	Missions to the lunar surface, at both polar and non-polar locations, testing autonomous landing and hazard avoidance, are required to retire this gap.	ALHAT/Morpheus work at JSC. So far, only one lunar robotic mission may have failed in a landing attempt due to terrain hazards (Luna 23). Is ALHAT needed, or did we get lucky with Surveyor missions? Not thought to be needed for human landers, as crew can control landing.
III-C-1 Lunar surface trafficability - modeling	Production of relevant lunar soil simulants. Geo-technical testing (especially trafficability) of prototype or test hardware in high fidelity regolith simulants. Not required for Apollo-zone exploration, but important for unexplored areas like regional pyroclastic deposits, the lunar poles, and melt sheets of large impact craters.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Over 20 different lunar simulants exist, world wide. Terrestrial testing in relevant lunar conditions, using multiple lunar simulants is required to retire this gap.	Over 20 different lunar simulants exist, world wide. University competition at KSC involving regolith manipulation. APL SSERVI node NASA ISRU types at KSC; NASA robotic types at JSC, Ames, JPL; Lunar Catalyst types such as Red Whittaker
III-C-2 Lunar surface trafficability - in situ measurements	Characterization of geotechnical properties and hardware performance during regolith interactions on the lunar surface.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, at both polar and non-polar locations, measuring geotechnical properties of the lunar regolith and conducting trafficability experiments in polar, pyroclastic, and young impact melt terrains are required to retire this gap	Requires a NASA (or NASA-funded partner) rover to traverse on the Moon. The Resource Prospector Project rover is the only NASA lunar rover in development and this project is not approved to go the Moon. NASA partners, such a Lunar Catalyst or Lunar Google X Prize may provide some useful information.

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III-D-1 Lunar dust remediation	Test conceptual mitigation strategies for hardware interactions with lunar fines, such as hardware encapsulation and microwave sintering of lunar regolith to reduce dust prevalence.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, at both polar and non-polar locations, testing dust remediation techniques, are required to retire this gap.	Larry Taylor sintering work at Univ. of Tennessee.
III-D-2 Regolith adhesion to human systems and associated mechanical degradation	In situ grain charging and attractive forces, and cohesive forces under appropriate plasma conditions to account for electrical dissipation. Analysis of wear on joints and bearings, especially on space suits.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, at both polar and non-polar locations, testing techniques to counter regolith adhesion, are required to retire this gap.	Gecko' space suit fabric at NASA-JSC. Electro-static 'curtain' experiments at NASA-KSC. DREAM2 SSERVI node. ARES STRATA-1 asteroid regoilth experiment on ISS.
III-D-3 Descent / ascent engine blast ejecta velocity, departure angle and entrainment mechanism - modeling	Laboratory modeling with plume and entrained simulant. Measurements of the extent of high velocity sandblasting of Surveyor 3.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**CLOSED**	Technology	Phil Metzger's work at NASA-KSC and UCF, and NASA's Morpheus lander tests at JSC and KSC fully addressed this strategic knowledge gap. This exploration technology gap can be retired.	Phil Metzger's work at NASA-KSC and UCF. Morpheus lander tests at JSC and KSC.
III-D-4 Descent / ascent engine blast ejecta velocity, departure angle and entrainment mechanism - in situ measurements	Multiple landings at the same location on the lunar surface may scour or damage systems and equipment already emplaced at that location. Ejected regolith velocity, departure angles, and energy in engine plume exhaust need to be measured in situ to better understand mitigation strategies, such as landing pads/berms, and separation distances between landing zones and operational zones.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, at both polar and non-polar locations, equipped with LIDAR type instruments to measure velocity and direction of blast ejecta, are required to retire this gap.	Phil Metzger's work at NASA-KSC and UCF. Morpheus lander tests at JSC and KSC. ChangE-3 paper

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III-E Determining near-surface plasma environment and nature of differential electrical charging at multiple lunar localities (includes PSRs)	The lunar near-surface electrical field and plasma environment is poorly known due to lack of direct, long term observations. Significant questions remain as to the degree of charging of hardware on the lunar surface, particularly night-side of the lunar terminator. Also, surface and surface-placed objects may undergo large changes in potentials during passages of solar storms. Direct observation is required in order to understand the variations of the electrical 'ground' defined by the plasma currents to an object placed on the surface. In PSRs, the lack of an obvious charge reservoir (i.e., low conductivity surface and obstructed plasma) suggests the possibility of poor electrical dissipation for tribocharging objects like drills, and rover tires. A surface mission would directly complement LADEE.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, at both polar and non-polar locations, measuring the near-surface plasma environment, are required to retire this gap.	CRATER instrument on LRO, LADEE and the ARTEMIS spacecraft, have provided data on the radiation and plasma envirnoment near the Moon. Electrometer on wheel of Resource Prospector.
III-F-1 Energy storage - non polar missions	Non-polar regions experience 14 Earth-days without sunlight; needs for entire lunar night in the 100s to 1000s kW-hrs; batteries will be prohibitively heavy.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to non-polar locations on the lunar surface, using energy storage systems, are required to retire this gap.	Energy storage technolgy work at NASA-GRC (Bob Cataldo et al.).
III-F-2 Energy storage - polar missions	Polar missions may be positioned in areas with extended solar availability; blackouts may extend to 3-5 days requiring 100s of kW-hours; batteries will be prohibitively expensive.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to polar locations on the lunar surface, using energy storage systems, are required to retire this gap.	Energy storage technolgy work at NASA-GRC (Bob Cataldo et al.).

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III-F-3 Power generation - non polar missions	Non-polar missions will require 10s to 100s of kW via deployable solar arrays or nuclear power systems on the lunar surface. Of particular concern is providing power through the lunar night.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to non-polar locations on the lunar surface, using power generation systems, are required to retire this gap.	Power generation technolgy work at NASA-GRC (Bob Cataldo et al.).
III-F-4 Power generation - polar missions	Low grazing angles of sun light at the lunar poles requires solar arrays with rotational tracking, preferably on a high mast; or nuclear power systems on the lunar surface.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to polar locations on the lunar surface, using power generation systems, are required to retire this gap.	Power generation technolgy work at NASA-GRC (Bob Cataldo et al.).
III-F-5 Lander propellant scavenging	Determine the efficiency of extracting residual oxygen from tanks in lunar landers. Variables include propellant settling in 1/6g, and LOX-He separation.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, testing propellant scavenging techniques, are required to retire this gap.	Unknown if there are NASA activities addressing this gap. Need to talk to Jerry Sanders at NASA-JSC. Possible Boeing ISRU work in progress.
III-G Test radiation shielding technologies	Protecting human crews beyond the magnetic fields of the Earth from space radiation is critical. In addition to Earth-based testing, could be further accomplished during lunar robotic missions.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions beyond low earth orbit (LEO), in cis-lunar space or on the lunar surface, testing radiation shielding technologies and operational approaches, are required to retire this gap.	CRATER instrument on LRO, and the ARTEMIS spacecraft, have provided data on the radiation envirnoment near the Moon. Crossed-reference to Theme 2.
III-H Test micrometeorite protection technologies	Need to develop experimental data for the range of micrometeorite impactors and impact energies expected in the lunar environment. Data to be used for the development of improved hydrodynamic codes for impact shielding, which can in turn be tested in terrestrial gun facilities. Testing these technologies could be done during lunar robotic missions.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, measuring micrometeorite impacts on instrumented sensors, are required to retire this gap.	Gun labs at NASA Ames and JSC. JSC Astromaterials Research and Exploration Science (ARES) Hypervelocity Impact Technology (HVIT) group work.

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III-I Lunar mass concentration and distributions (ie.., graviational anaomalies)	Understanding of the lunar gravity field affects the accuracy of navigation predictions, the ability to do precision landing and the stability of spacecraft left in orbit for long periods w/o active orbit maintenance (e.g, the stability of the Apollo 15 ejected sub-satellite (months) to similar hardware on Apollo 16 (2 weeks). The SELENE, LRO, and GRAIL missions have significantly improved our experience with stable orbits.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**CLOSED**	Exploration Science	NASA's GRAIL mission fully addressed this strategic knowledge gap. This exploration science gap can be retired.	See the latest GRAIL lunar gravity model and journal articles on mass concentration, crust thickness, etc.
III-J-1 Fixed habitat	Human explorers and workers on the Moon will require pressurized habitats to live in while on the lunar surface. For short duration missions, human crew may be able to live in their lander vehicles similar to the Apollo missions.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, using fixed habitats, are required to retire this gap.	Desert RATS 2010-2011 JSC/EA habitat; ISS modules. HERA habitat simulator at JSC.
III-J-2 Mobile habitat	The Apollo J-missions clearly showed the benefits of mobility when it comes to human exploration of a planetary surface. Pressurized rovers used as short-duration field camps, or larger mobile habitats for longer duration exploration of a large region of the Moon may provide an exploration architecture that is not necessarily fixed to one point on the lunar surface.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, using mobility systems and mobile habitats, are required to retire this gap.	Desert RATS 2010-2011 efforts; JSC/ER small pressurized rover; JSC/EA habitat; JPL Athlete. Continuing JSC efforts on multi-mission space exploration vehicle (MMSEV).

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III-J-3 Semi-closed life support	While initial, short-term missions to the Moon may get by with open life support systems, the Earth-moon distance will make the logistics of this type of system unsustainable for long periods of time. The ISS has incorporated aspects of closed life support systems, and extending their use to the Moon seems to make sense.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, using closed or regenerative life support systems, are required to retire this gap.	Regenerative life support components are on ISS. However, a complete regenerative life support system has yet to be employed in space. Most, if not all, NASA technology development of bioregenerative life support efforts using plants for oxygen, water, and food production has been stopped.
III-J-4 Human mobility	Human crews on the Moon need spacesuits to explore and work out on the luar surface. Also, the Apollo J-missions clearly showed the benefits of mobility when it comes to human exploration of a planetary surface. Unpressurized rovers like the Apollo LRV, or one-person Segway-like vehicles could be used for local transportation, while pressurized rovers could provide for longer multi-day traverses.	Enabling for all human missions to the Moon.	**OPEN**	Technology	Missions to the lunar surface, using multiple types of human mobility systems, are required to retire this gap.	Desert RATS 2008-2011 efforts; JSC/ER scout, chariot, and small pressurized rovers. Continuing JSC efforts on multi-mission space exploration vehicle (MMSEV). Continuing JSC efforts on Z-2 suit. Need info on lunar PLSS.